AUTOMATIC ELECTRONIC CONTROL OF HEAT

TRANSFER TO A FRACTIONAL DISTILLATION COLUMN

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by

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INTRODUCTION

The aim of this thesis project is to apply the knowledge gained by the author toward the solution of a practical problem in the application of servomechanisms. The approach has been made through laboratory experimentation rather than through a theoretical mathematical investigation. All electronic circuits used have employed only well established principles in electron theory.

A secondary purpose is to emphasize the importance of automatic control, or more precisely, servomechanisms, in the peacetime pursuits of industry. After undergoing extensive wartime development, electrical servos for automatically holding a setting, a movement, a process or physical characteristics within design limits are now available in a great variety of arrangement, size and application (see Figure 1).[1] The underlying servomechanism theory which steered the ships and torpedoes, aimed guns and performed scores of exacting jobs on aircraft from operating the instruments and regulating temperatures, air pressures and speeds to taking over the pilots' job of flying the plane, could also be applied to the control, regulation and recording of data in industry.

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[1] C. H. Roe, "Perhaps You Can Control It With An Electric Servomechanism", Electrical Manufacturing, August, 1946, pp. 102-106, 220, 222, 224, 226, 228.

FIGURE 1

WHAT SERVOMECHANISMS CAN DO

Essentially controlling or regulating devices, servomechanisms have been applied, or it has been proposed to apply them, to the control of:

Water level in boilers, tanks, sumps.

Liquid level in processing vessels.

Pressure, temperature, velocity, speeds of translation or of rotation, voltage, current, frequency and other physical characteristics.

Temperature and rate of air flow in drying kilns and elsewhere.

Registration or positioning of sheets or webs of paper or cloth, threads, filaments, etc., for printing, cut-off, or other operation.

Profiling operations of machine tools and cutting machines by means of templates, outlines on paper, models, etc.

Screw-down of rolls in steel mills.

Rate of feed, tension or rewind of paper, cloth, steel sheet, etc., in multiple-stand machines of various kinds.

Feeds on machine tools.

Rates of acceleration in centrifuges and other high-speed loads.

Remote instruments.

Process programs, particularly operations in oil refineries, chemical production and food processing plants.

Laboratory operations in testing or measuring certain kinds of equipment.

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CHAPTER I

GENERAL HISTORY AND THEORY OF SERVOMECHANISMS

Servomechanism theory was established in this country when Dr. H. L. Hazen of the Massachusetts Institute of Technology published his classic paper in 1934.[2] The theory was amplified by others and important contributions were made, but there are still very few books in existence which deal comprehensively with the subject.

Servomechanisms, or servos, are variously defined. S. W. Herwald of Westinghouse Electric Corporation says that a servomechanism is in general any closed-cycle regulated system that is controlled by a difference of quantities.[3] Gordon S. Brown and Albert C. Hall of Massachusetts Institute of Technology have a similar definition which says that a servomechanism is a power amplifying, automatic control-system characterized by the presence of a control element that is actuated by some function of the difference between the response desired of the system and its actual response.[4]

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[2]H. L. Hazen, "Theory of Servomechanisms", Journal of the Franklin Institute, vol. 218, No. 3, September, 1934..

[3]S. W. Herwald, "Considerations In Servomechanism Design", Trans. AIEE, vol. 63, p. 811, December, 1944..

[4]Gordon S. Brown and Albert C. Hall, "Dynamic Behavior and Design of Servomechanisms", ASME paper No. 45-A-20, November, 1945.

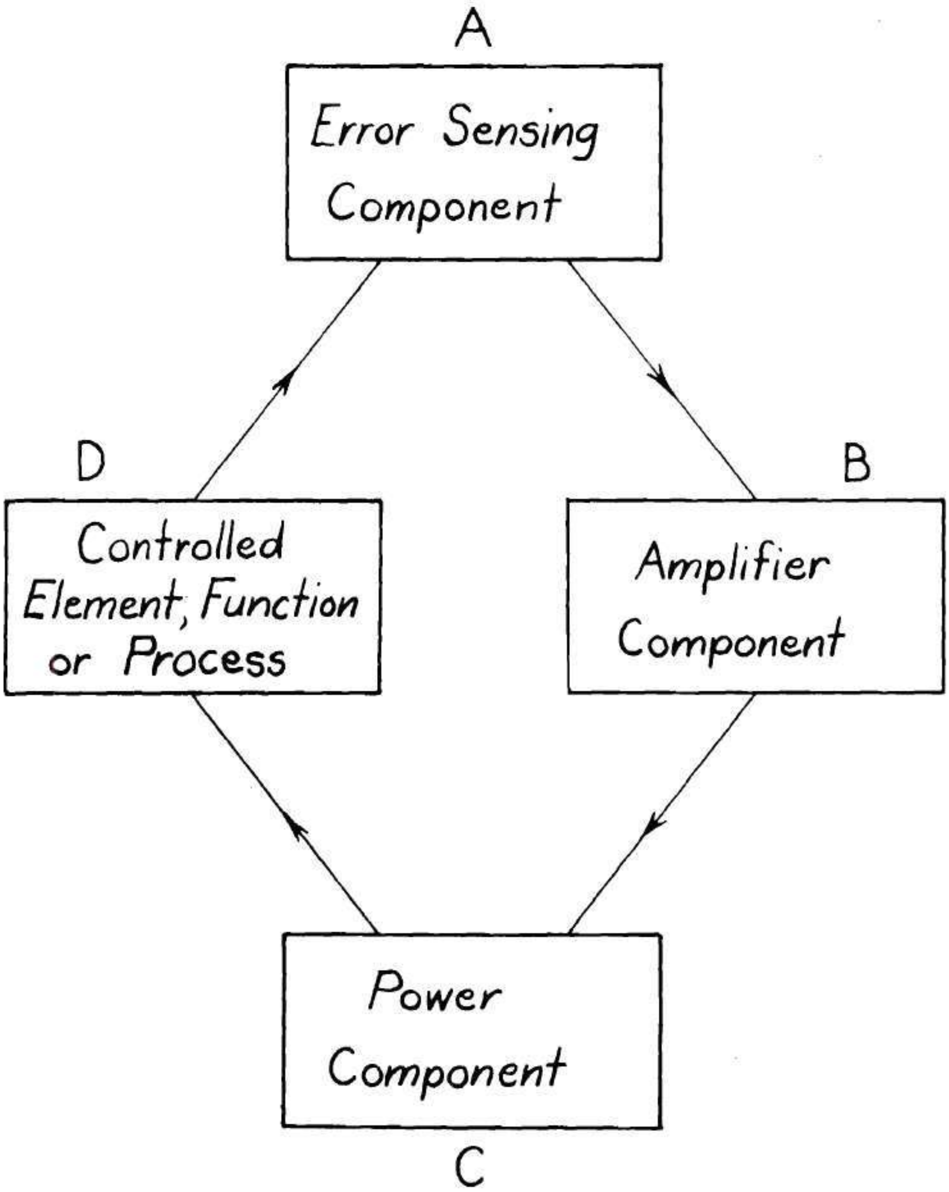

Figure 2
Servomechanism Block Diagram

The essential elements of a servomechanism are represented in the block diagram in Figure 2. Block D is the thing to be controlled - it may be the direction in which a ship is headed; the level, rate of flow, temperature, pressure or pH value of a fluid; the speed, voltage or current of an electrical apparatus; or the position, rate of travel or other feature of some material undergoing processing. To regulate this quality, whatever it may be, is the purpose of the servo. The error-, discrepancy-, or divergence-sensing component A contains the standard or the reference against which the performance of D is continuously compared. The comparison brings out the difference, or error, of the two quantities. The standard or reference may itself be adjusted manually from time to time or continuously or may be subject to change through other means. Nevertheless, it is the servo's job to follow it and to keep D in conformity. Component A begins to operate when this error exceeds a minimum value. The feed-back connection from D to A is what makes this a closed system; it automatically carries the information back to A that the error previously sensed is being corrected and it operates to cut off the correcting action as the error is reduced to minimum proportions..

As a result of the error-sensing function of A, an impulse, or signal, or a continuous influence passes from A to B, where it may be amplified but, in any case, where it actuates an appropriate device to enable it to control the power unit at C in accordance with the requirements indicated by the signal received at B. The power unit at C, under control from B, goes to work on D to bring about a correction of the error sensed at A. As this is done the feed-back connection from D to A brings about a re-setting back to zero of the error-sensitive component, thus tending to put a stop to the operation when the desired conditions have been re-established.

Component A may have a band or range of insensitivity in which it cannot transmit the essential signal to B. This is called a dead zone and its measurement is sometimes designated as the threshold value. It is directly analagous to mechanical back-lash.

There is always a lag in time or phase between the perception of the error at A and the report through the feedback from D that the error has been corrected. This lag is inherent. However, it is desirable to control this lag closely not only to keep it as small as possible but also to insure that it is always within definite limits of phase relationship. It is important that it always be subtractive from the input signal because, if it should become additive, the system would be regenerative and unstable.

It may happen that the correction at D as a result of the functioning of C may overshoot the required amount before the feed-back can stop the operation by reducing the error sensed at A. Over shooting may result in oscillation or hunting. This is not always undesirable and is sometimes purposely designed-in the controller. This may be done in the case where electrical contacts are used and it is desired to keep them "alive", guaranteeing readiness for further action. Oscillation is brought about by certain well known relationships and values of characteristics and it is part of every design operation to check for such a possibility, whether it is desired or not.

Basic servo theory is a paradise for an enterprising mathematician. The feed-back principle, causing a reduction in the difference sensed at A while this difference is still originating the action which brings about that reduction, can readily be seen to require handling by methods of the differential calculus. Also, in studying servos sensitive to small differences in rates of change, such as those in acceleration control, differential equations of as high as the seventh or eighth order become apparent. Most of the mathematical tools such as Bessel's functions, Heaviside's expansion and operational calculus, the Laplace transform, Nyquist's criterion and Fourier analysis are brought into common usage as the full possibilities of servomechanism are explored.

Although there is plenty of opportunity for the use of mathematical skill in designing servomechanism, it would be a mistake to represent such skill as essential. With the increasing availability of standardized components, it is often possible to put together the various parts, matching them up with only a good knowledge of electrical engineering and physics. Operating characteristics can be determined by laboratory tests, all without making the calculations which may still be necessary when designing a control with really novel features for which ready-made components cannot be secured.

CHAPTER II

PRESENTATION OF CONTROL PROBLEM

The specific objective of this thesis project is to design, construct, and put into operation an automatic electronic control system which will prevent heat transfer to or from a fractional distillation column. This control is required in order to approach adiabatic operation of the column while the column undergoes the temperature changes in the distillation process.

The distillation column is constructed of four feet of 25 mm. diameter glass tubing mounted vertically. In order for the fractional distillation process of a series of vaporizations and condensations to occur uniformly throughout the column, no heat transfer from the column is permissible. This heat transfer is to be prevented by surrounding the distillation column with another glass column or jacket which is held at the same temperature as the column by means of electric heating coils. Still another glass column or jacket is placed over the heating coils, insulating the coils from air currents. The annular space between the column proper and the inner jacket is large enough so that the temperature in the column is not affected directly by the heating element, but rather is controlled by the annular space acting as an air bath.

The control problem is to provide automatically to these heating coils the electric power necessary to prevent any heat losses from the column. The solution of the control problem may be divided into four main parts: (1) To detect the temperature differential between the column and the surrounding jacket, (2) To convert this temperature differential into an electrical signal, (3) To amplify this electrical signal into a controlling magnitude, and (4) To use this amplified signal to regulate the power supplied to the heater coils.

CHAPTER III

METHOD OF REACHING OBJECTIVE

A. <u>Survey of Literature Dealing With Similar Problems of Control</u>.

It is always wise to investigate the efforts of others when tackling a problem in order to profit by their experience. Therefore, the first step toward arriving at a solution to the control problem was to make a survey of literature dealing with similar problems of control.

After investigating several articles on temperature control, it was found that in most applications on-off relay control circuits were employed. While this method of control is satisfactory for a majority of applications, it is not suited for the continuous temperature control necessary to insure proper column operation. Our problem requires that no heat transfer occur at any time. Relay control operation is such that the average heat transfer over a period may be zero, but heat may be gained or lost compensatingly from the column during this period. Other disadvantages of reviewed temperature control applications were that they lacked the sensitivity required, they operated with an adjustable but non-varying reference and they employed d-c amplifiers which are difficult to stabilize for high gain operation.

Continued reading brought forth the following possible continuous control applications:

(1) An electro-mechanical servo which will operate a rheostat or variac.

(2) An electrical circuit employing a saturable reactor in series

with the load.

(3) A grid controlled thyratron rectifier circuit supplying power to the load.

Any one of these systems would provide satisfactory control, but other features such as simplicity, compactness and availability and cost of the component parts must be considered. The electro-mechanical system was eliminated immediately as it presents a roundabout, inefficient solution to the problem. The second method is quite reasonable and received much consideration. Its disadvantages were the unavailability of saturable reactors and the fact that the controlling current was d-c. The grid controlled thyratrons seemed to offer the smoothest, most direct continuous control. Also, suitable thyratron tubes were available in the laboratory.

After the power control element was selected, the matter of detecting the temperature differential between the column and jacket presented itself. Temperature changes cause various changes in the electrical properties of metals. The most common of these properties is the change of resistance with temperature. Another electrical indication of temperature may be obtained from thermocouples from which an output voltage proportional to temperature may be obtained. The disadvantages of thermocouples arise in amplifying the d-c signal to a controlling magnitude and in the fact that it indicates temperature at the point of application only. The d-c signal amplification may be accomplished in two ways, both of which were considered unsatisfactory. As was previously mentioned d-c amplifiers are difficult to stabilize, especially a multistage, high gain amplifier which would be required to obtain the desired control sensitivity. The other possibility is to convert the d-c signal into an a-c signal by means of a vibrator or polarized interrupter. This a-c signal could then easily be amplified by a high gain a-c amplifier of conventional design, the stability of which is fairly well assured.

It is apparent from the discussion that an a-c error signal is desirable. It is also apparent that a comparison of the average temperature over the controlled area with the average of the reference area provides a more satisfactory control than point comparisons. It follows that the best indication of a temperature differential between the column and jacket would be derived by covering the two areas with a metal of high temperature coefficient of resistivity and comparing the resistance to a-c current flow. A compromise of this method is to wind the columns with fine wire and compare the resistance of the control area and the reference in an a-c resistance bridge.

The a-c error signal from the bridge could then be amplified to a controlling magnitude with little difficulty by a conventional high gain a-c amplifier.

B. Selection of Type of Control.

After reviewing current literature on temperature control, it was decided that a grid-controlled thyratron circuit would be a reliable and relatively simple control circuit to supply power to the heating coils. Since the power regulation was to be obtained through shifting the phase of the thyratron grid voltage, it was necessary to have an amplifying circuit between the error-sensing device and the thyratron grids to boost the error voltage to a controlling magnitude.

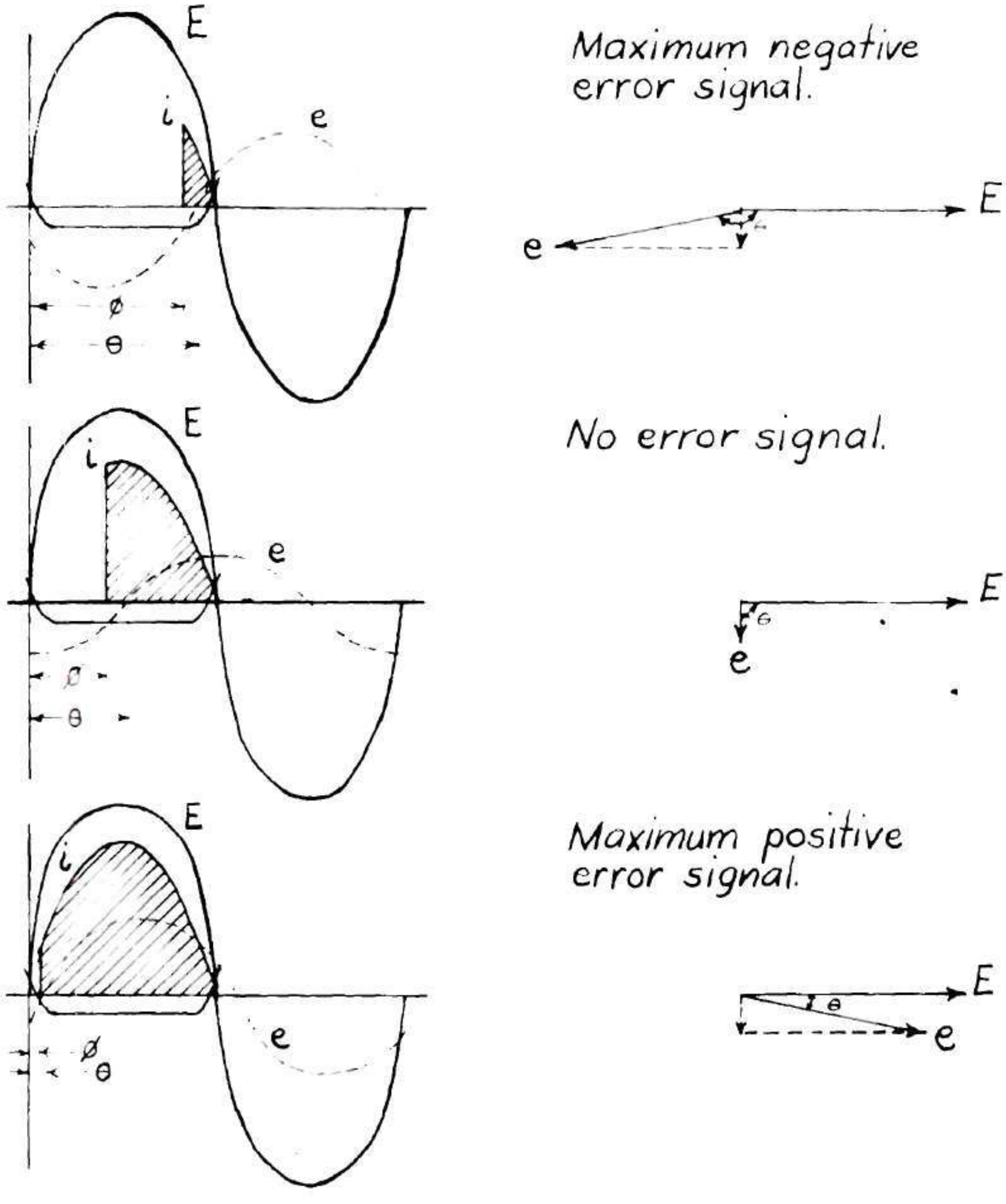

Figure 3

Phase-Shift Control of Thyratron Conduction Period

The temperature differential or error between the column and jacket was detected by the change of resistance with temperature of wire windings on the column and jacket. The windings of each were in separate arms of a resistance bridge such that any change of resistance of a column winding caused a bridge unbalance until the jacket winding resistance reached the same value through a corresponding temperature change. In order to keep the temperature differential within several hundreths of a degree centigrade, it was necessary to be able to detect and amplify a fraction of a millivolt to a controlling voltage magnitude of about 50 volts. This was accomplished with a high gain, two-stage amplifier designed to amplify 60 cycle per second error voltages. The number of stages was kept to a minimum to reduce the effects of stray pickup and random noise.

The phase shifting network in the thyratron grid circuit is formed by the addition of two vector voltages - one voltage being fixed in magnitude and lagging the thyratron anode voltage by 90 degrees, the other voltage being variable in proportion to the bridge unbalance and either in phase or 180 degrees out of phase with the anode voltage depending upon the direction of bridge unbalance (see Figure 3). By controlling the firing angle of the thyratrons the average current over a cycle can be regulated from almost zero to maximum tube conduction. The firing angle or conduction point of the cycle is controlled by adjusting the phase angle between the plate and grid potentials. The operation of the system is illustrated in Figure 3. The grid-cathode potential, e, lags the plate-cathode potential, E, by the angle θ, as indicated in the voltage vector diagram. When the grid potential equals the critical grid breakdown potential at the angle ϕ, conduction begins and continues until the plate potential falls below the value to maintain conduction.

The servo loop is now complete. Unbalance of the resistance bridge provides the error signal (Block A, Figure 2) which passes through an amplifying unit (Block B) before entering the power unit (Block C) which regulates the power supplied to the heating coils (Block D). The temperature change brought on by the heater coils tends to correct the bridge unbalance, thus closing the feedback loop from D to A.

C. Design and Construction of Components.

1. Wire Windings. It was decided that the most direct method for both detecting and converting the temperature differential between the column and jacket into an electrical signal was to use a wire winding of material with a high temperature coefficient of resistivity. Pure iron and nickel wire were the practical choices in available material, having a temperature coefficient of resistivity of 0.00650 and 0.00537 from 0-100°C and 20-100°C respectively.[5] Since 99.8% pure iron wire of proper size (No. 36, 5 mils diam.) was readily available, it was chosen for use as the temperature sensitive winding. Size No. 36 was selected because the small mass of the wire enables the winding to follow temperature changes rapidly, yet the wire is large enough to withstand rough handling of the column.

Since a variable temperature gradient is present along the height of the column, it is necessary to compromise on the extent of temperature matching that is to be accomplished between the column and the jacket. It was decided that matching the average temperature of both the top half

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[5] Ovid W. Eshbach, Handbook of Engineering Fundamentals, (New York: John Wiley and Sons, 1946), pp. 1-125.

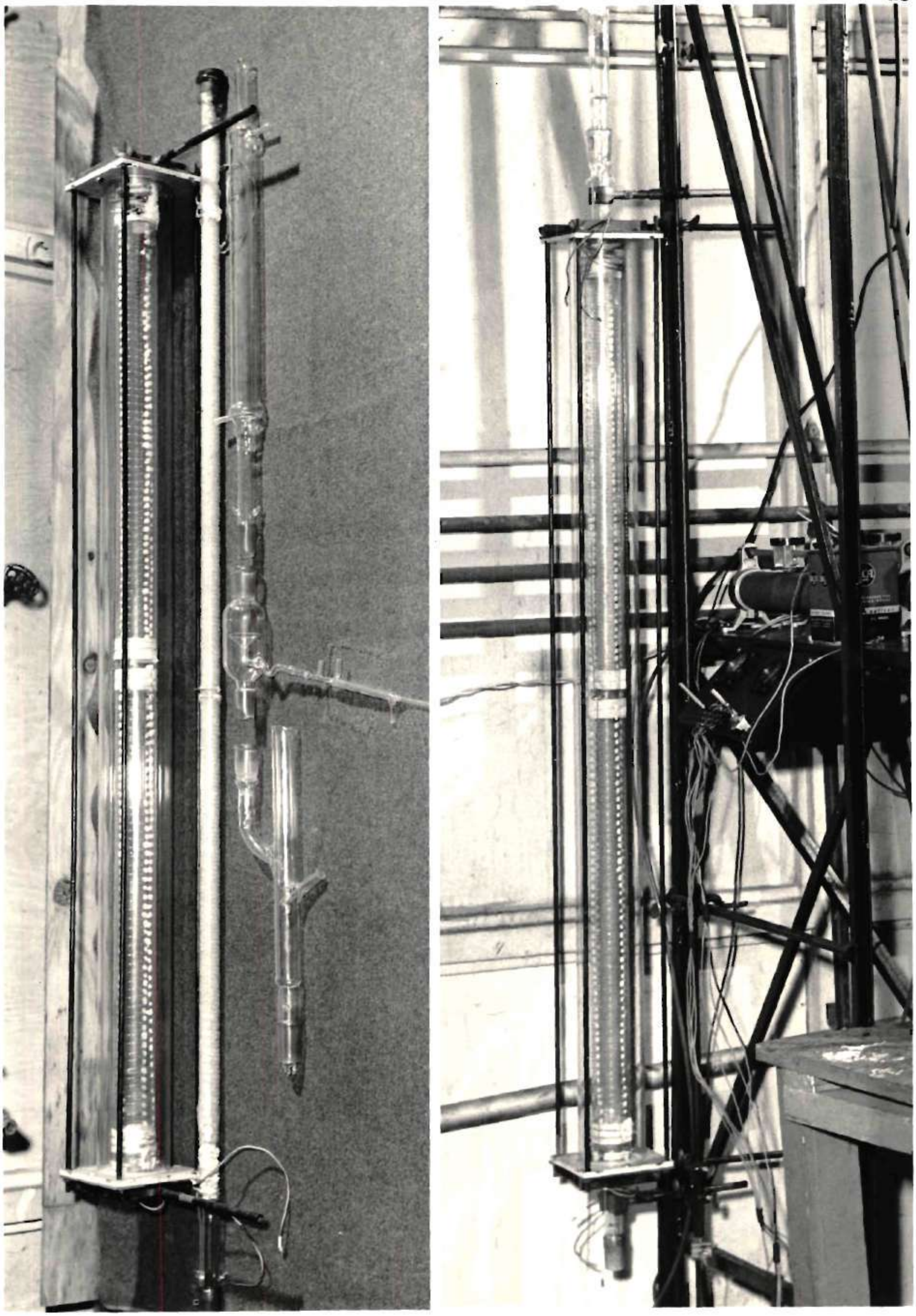

FIGURE 4

and the bottom half of the column and jacket would eliminate most of the heat transfer from the column. Consequently, the column was wound with two separate windings of approximately 35 feet of pure iron wire with a resistance of 0.71 ohms/foot. The turns in the windings were spaced 5 mm. apart on a 25 mm. diameter tube and were so arranged that the terminals were at the ends of the column as shown in Figure 4. The double winding with oppositely wound halves in each half of each column minimized the effects of inductance in the windings. The jacket temperature sensitive windings were made in a similar manner using the No. 36 pure iron wire. Since the diameter of the jacket was approximately twice (48 mm.) that of the column, the windings were spaced 10 mm. apart in order to get a total wire length of about 35 feet. (see Figure 4). Sauereisen cement was used to secure the turns in position on the glass after winding, and asbestos tape was used to insulate the different windings from each other as they approached their respective terminal posts at the ends of the column. The terminal posts were made of a loop of No. 20 copper wire twisted together at the ends after passing around the column.

The heater windings on the jacket were made of No. 28 chromel A resistance wire and followed the same pattern of winding as the temperature sensitive element. The turns of the windings were spaced 10 mm. apart so as to fall equidistant between the turns of the temperature sensitive windings and were so arranged that the two ends were joined together for one terminal with a center tap as the other terminal such that there were two heater coils in parallel in each half of the jacket. This was done in order to give a total heater input of about 630 watts at 105 volts. It was calculated roughly (see Appendix) that the total heat loss from the

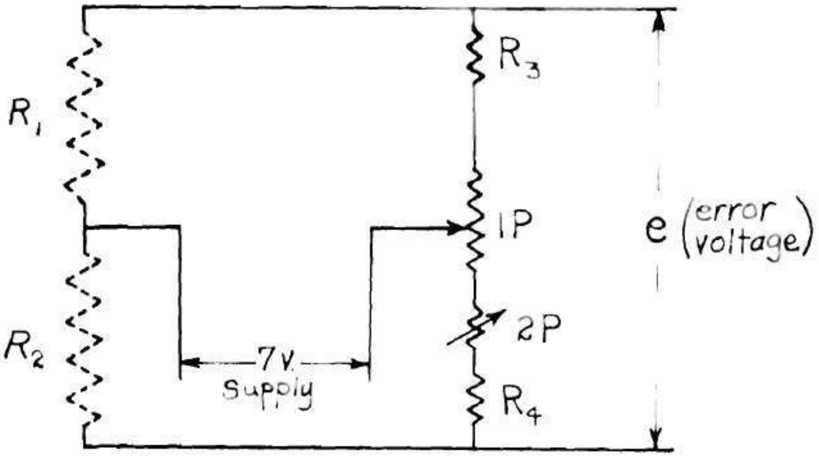

Figure 5
Resistance Bridge

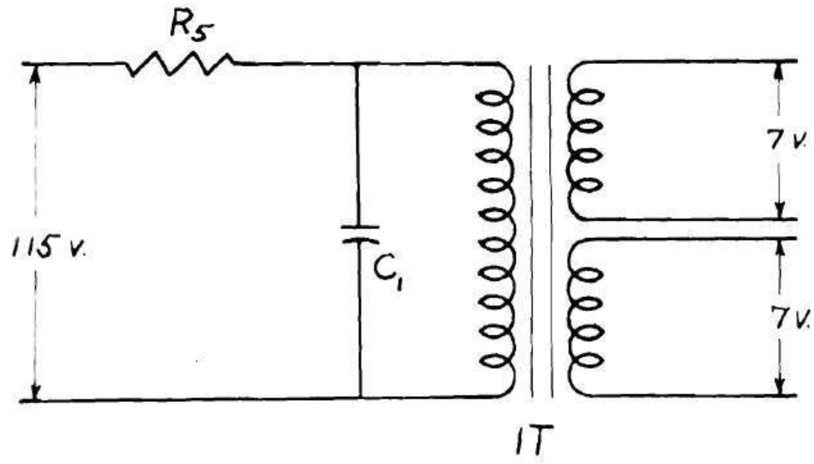

Figure 6
Bridge Phase-Shifted Voltage Supply

column under the most extreme conditions would not exceed 693 watts for normal operation at from 0°C to 200°C.

2. A-C Resistance Bridge. The column and jacket temperature sensitive windings were each connected in separate arms of a resistance bridge (see Figure 5). In the other two arms were wire wound resistors of 25 ohms each. Maximum bridge sensitivity was thus obtained as each of the four bridge arms contained approximately equal resistances. Balancing potentiometers - one for coarse and one for fine adjustments - were placed in the bridge arms containing the fixed resistors. It was necessary to construct slide wire rheostats of 0 to 0.15 ohm each to provide the fine adjustment necessary to balance the bridge. An indication of bridge balance is obtained from a voltmeter connected across the jacket heater terminals. The no signal heater voltage was measured to be about 62 volts. In order to obtain the accurate temperature control desired, it was found necessary to balance the bridge within 0.05 ohm or less than 0.1 millivolt unbalance.

3. High Gain A-C Amplifier. Since the resistance-coupled amplifier is the most widely used method of obtaining voltage amplification at audio-frequencies, its circuit (see Figure 7) was selected as the amplifying unit for this control system.[6] The basic circuit was obtained from the RCA Receiving Tube Manual and the majority of the values of the circuit components were selected from chart 8 on page 200 of the manual. 6SH7 tubes were selected, after making a survey of available pentode tubes in the laboratory supplies, because they offered highest

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[6] F. E. Terman, Radio Engineering (New York: McGraw-Hill Book Company, Inc., 1947), p. 230.

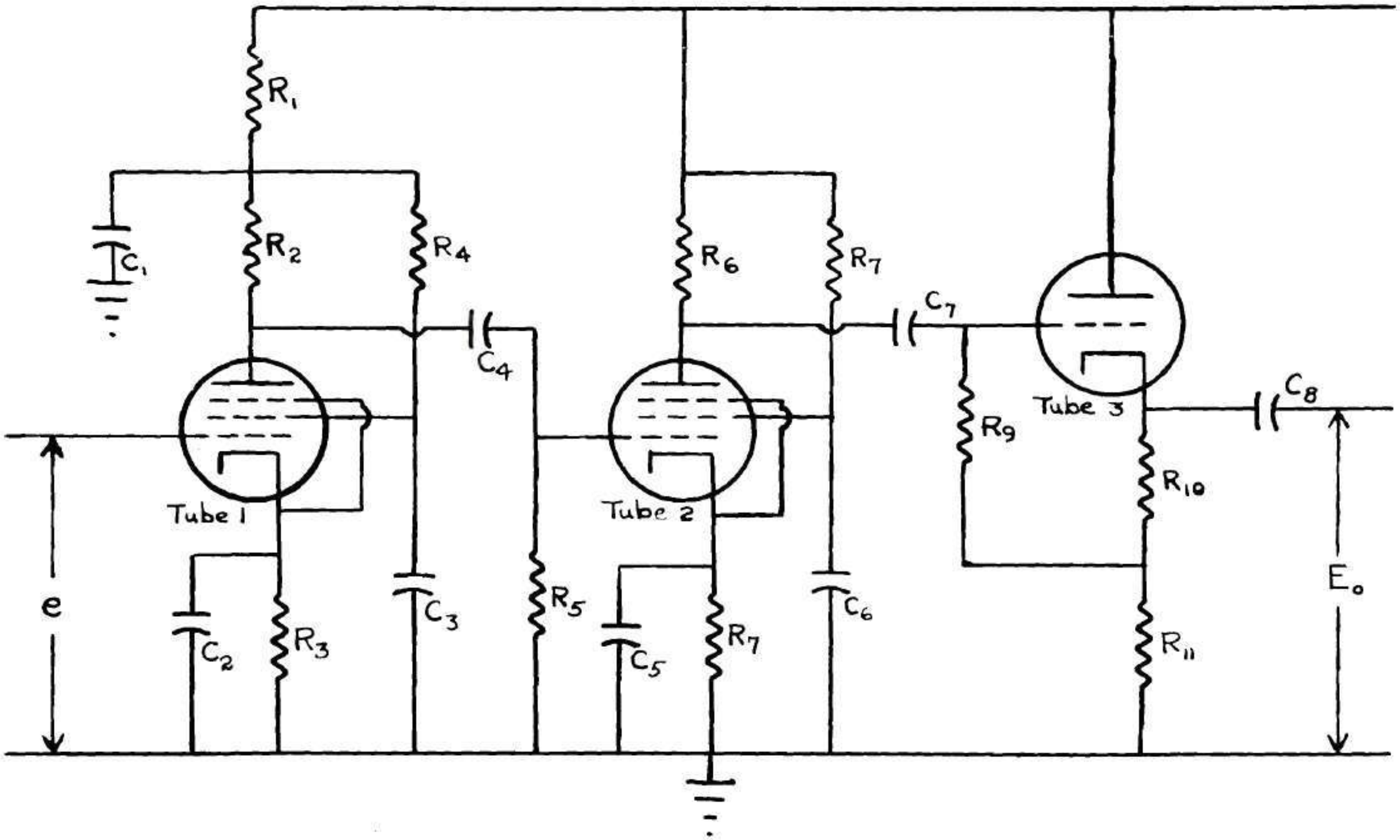

Figure 7

Resistance - Capacitance Coupled High Gain Amplifier

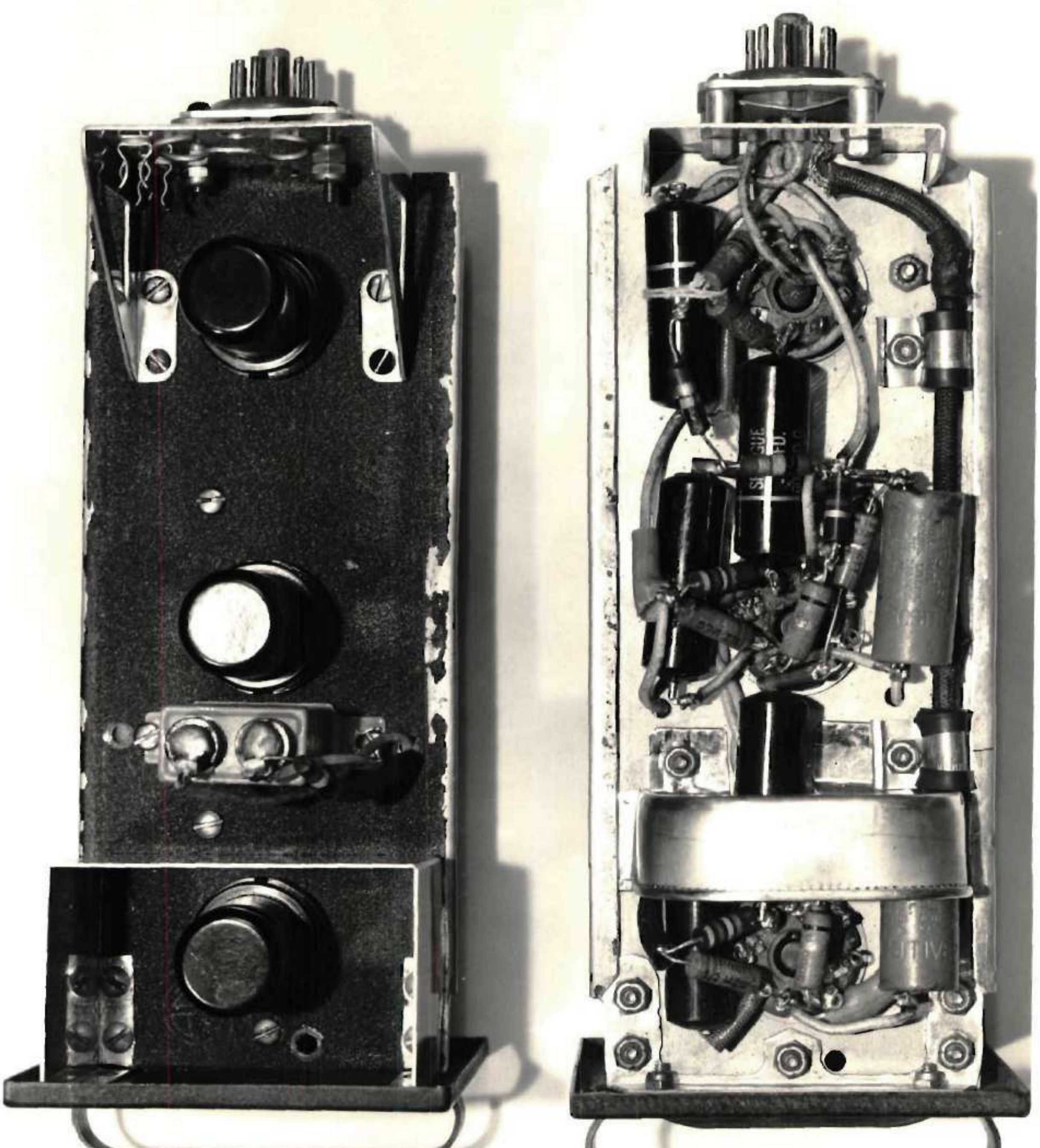

FIGURE 8

voltage amplification for the two stage amplifier which was desired. A 6J5 triode was added as a cathode-follower amplifier to match the amplifier proper to the load impedance. The cathode-follower acts as an impedance transformer which takes the voltage developed across a relatively high impedance, and, by applying it to the grid of the cathode-follower stage, transfers this voltage, only slightly reduced in magnitude, to a voltage across a relatively low resistance load. A high tube transconductance is necessary to make the equivalent output impedance of the tube small.[7]

It was found by experimentation that the amplifier stages, especially the first stage, must be well shielded (see Figure 8). Consequently, the amplifier was designed to operate in an aluminum box shield. In addition, the input lead to the grid of the first stage is shielded in wire braid grounded at the tube only and the entire first stage is shielded both top and bottom by can shields. This shielding effectively reduced stray pick up to a tolerable value of about four volts on the output with no signal on the input. In order to obtain satisfactory circuit operation, some slight modifications to the basic RC amplifier circuit and circuit components were necessary because of the difficulty encountered in amplifying a sixty cycle per second signal. It will be noticed that it was necessary to isolate the plate supply voltage to the first stage from the other plate supply by an RC filter section. Through measurement it was found that a maximum unclipped output of 50 volts could be obtained from the amplifier with a total voltage gain of about 70,000. This measured gain compares favorably with the expected circuit gain per

[7]Ibid, p. 310.

stage given in chart 8 on page 200 of the RCA Receiving Tube Manual.

4. Grid-Controlled Thyratron Circuit. The grid-controlled thyratron circuit consists of two FG-27A thyratrons connected in inverse-parallel in order to provide full wave transmission (see Figure 9). The anode supply voltage is 115 volts a-c. The two voltages which add together to form the grid voltage are induced into the grid circuit through 1 to 1 ratio center-tapped transformers. As was previously discussed, it was necessary to shift the phase of the fixed grid voltage component 90 degrees lagging the anode voltage. This phase shift was accomplished by tapping the voltage from the center-tap and between R and C of the RC loaded transformer. It was also found that an inductance was required in series with the amplified error signal in order to improve the output wave shape of the loaded amplifier. The inductive load in the transformer secondaries was reflected into the primaries as capacitance which highly distorted the output wave of the amplifier. Transformers were required in the grid circuits to isolate the grid voltages from a common ground.

5. Voltage Regulated Power Supply. The design of electronically regulated power supplies has become fairly well standardized. A typical circuit was used in this control system and is shown in Figure 10. It was taken from <u>Electronic Instruments</u>[8] with modifications to the input filter and the addition of a potentiometer on the grid of the difference amplifier tube to adjust the magnitude of the output voltage. The operation of the circuit is essentially the following: The source of unregulated

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[8] I. A. Greenwood, J. Vance Holdam and Duncan MacRae, Electronic Instruments (New York: McGraw-Hill Book Company, Inc., 1948), p. 551.

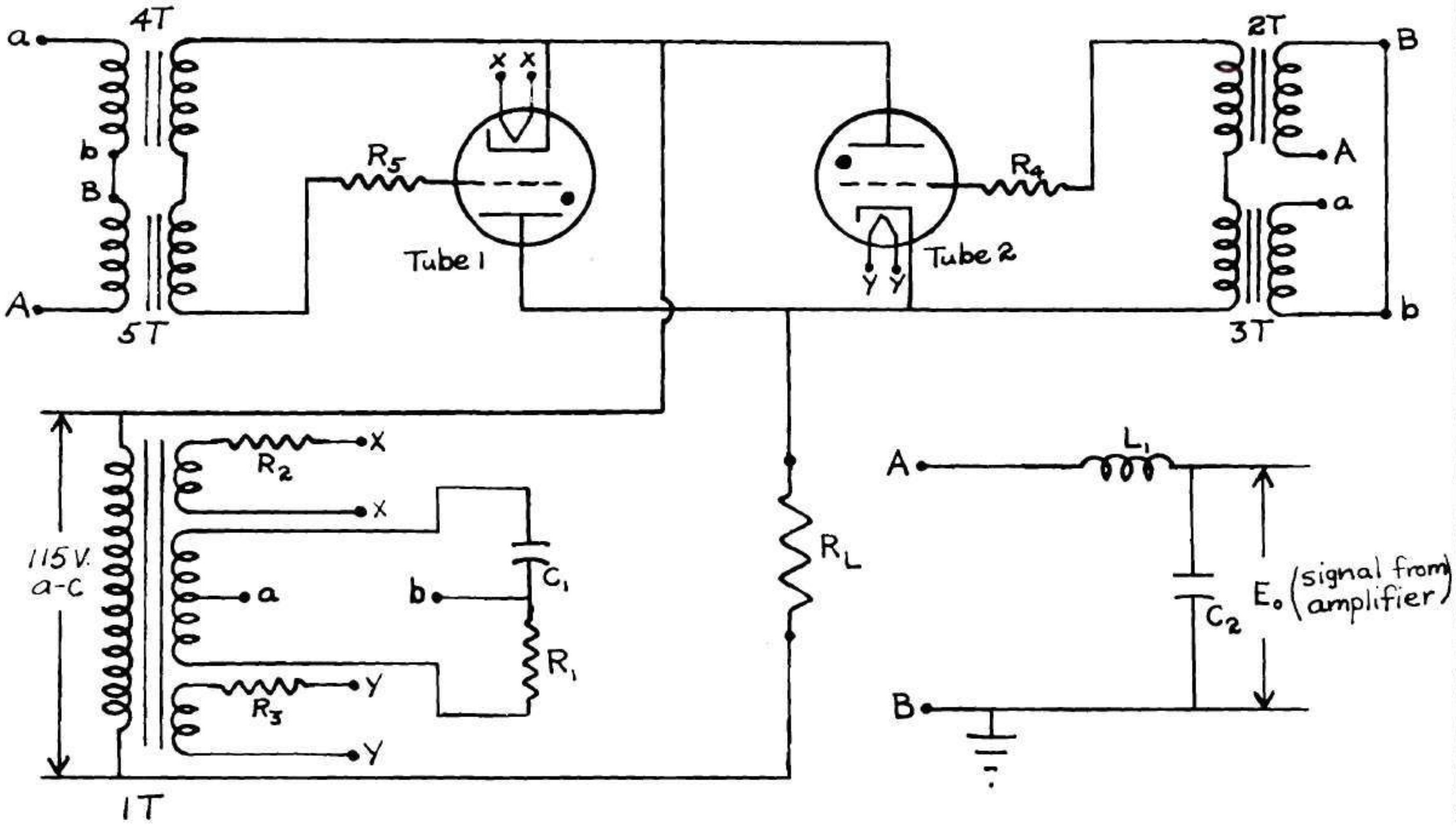


Figure 9
Grid-Controlled Thyratron Power Unit

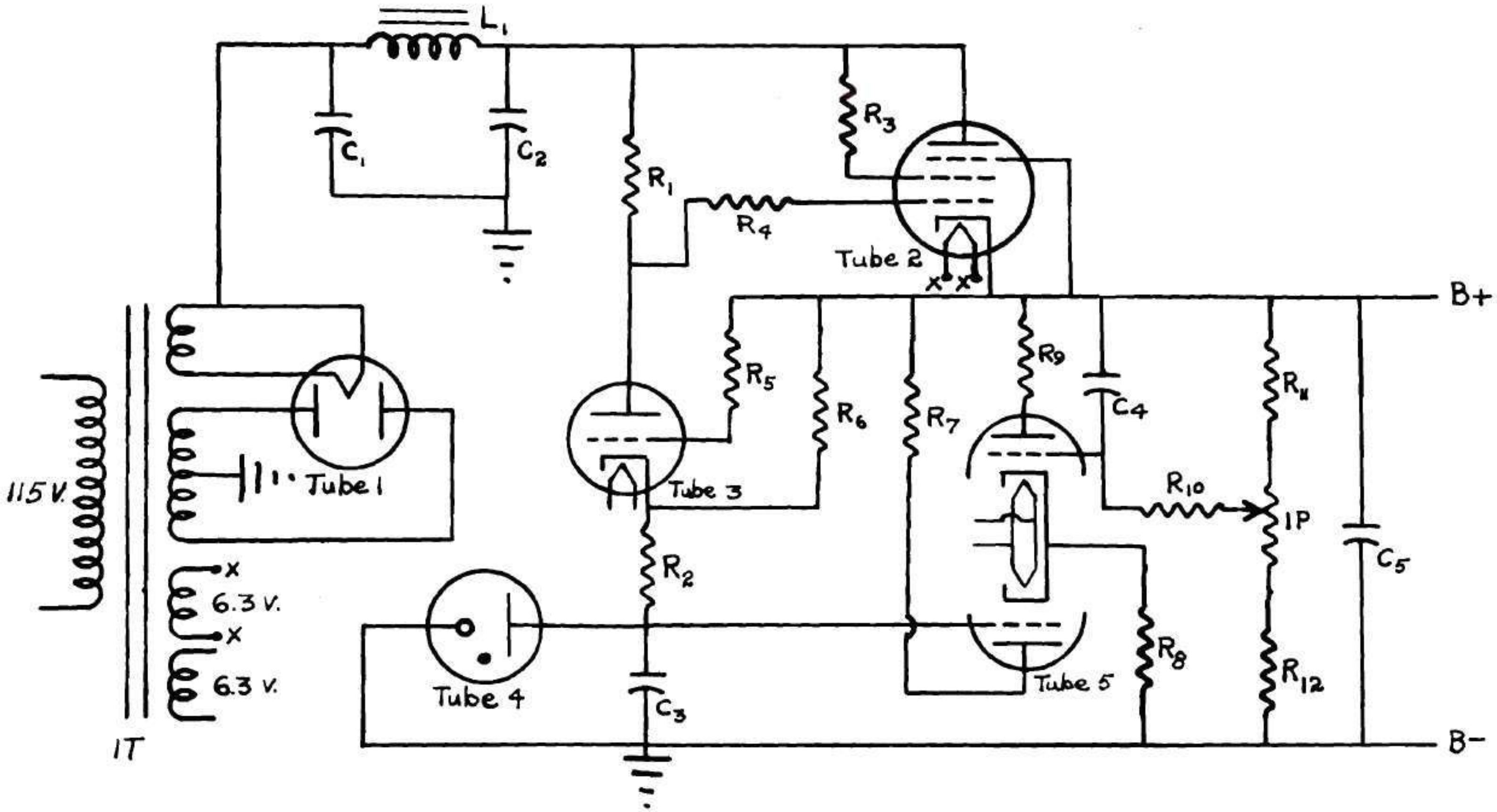


Figure 10

Voltage Regulated Power Supply

voltage from the rectifier and filter is applied across the input terminals of the regulator. The unregulated d-c voltage is fed through the series control tube, 6L6, to the output circuit. The regulating action is obtained by comparing a fixed fraction of the output voltage with a standard voltage source, VR105. Any difference between the two is applied degeneratively after amplification by a high-gain d-c amplifier to the control grid of the series tube. Since the voltage regulation required is to provide a practically ripple-free output and almost perfect regulation, the gain of the d-c amplifier must necessarily be high. This was accomplished by using a two stage difference amplifier employing 6SL7 tubes.

The values of the components of the input filter to the regulator were arrived at by experimentation to provide 265 volts regulated d-c with negligible ripple while supplying 50 ma. of current. The ripple at rated load was undetectable with full gain on a cathode ray oscilloscope. The voltage regulation was quite good with no apparent changes in magnitude at rated load.

The voltage supplies to the resistance bridges were also obtained from the power supply unit. However, they were obtained from a separate transformer and phase shifting network (Figure 6). It was found necessary to shift the phase of the bridge voltage to about 30 degrees lagging the line voltage in order that the output of the amplified error voltage would be in-phase or 180 degrees out of phase with anode voltage on the thyratrons. The phase shift in the amplifier was about 30 degrees leading. This 30 degree phase shift was a compromise between the two amplifier phase shifts which varied somewhat over the operating range and were slightly different for each amplifier.

It was necessary to isolate the two bridge supply voltages to prevent interacting of the bridge error signals since the corresponding corners of the two bridges were not necessarily at the same potential. A bridge supply of seven volts was selected as the maximum voltage which could be used without causing the temperature sensitive windings to become excessively heated by internal current flow. Seven volts on the bridge causes a heat dissipation of about 0.6 watts in each arm of the bridge. This heat generation was considered negligible when distributed over two feet of 25 mm. glass column. Since the bridge sensitivity is directly proportional to the bridge supply voltage, it is advantageous to keep this supply voltage as large as possible.

CHAPTER IV

CIRCUIT ANALYSIS

Since the control information originates with the change of resistance of a wire with temperature, it may be well to analyze this change first. Assuming a linear variation between resistance and temperature, the following formula holds true:[9]

$$R_2 = R_1\left[1 + X_1\ (T_2 - T_1)\right] \tag{1}$$

Where R = resistance in ohms.

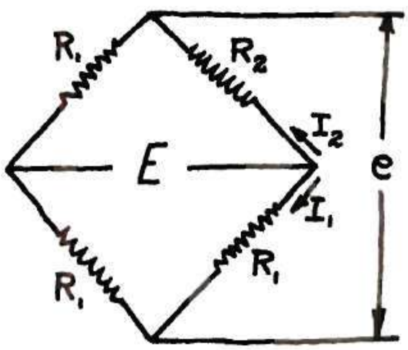
T = temperature in °C.

X = temperature coefficient of resistivity.

The temperature coefficient of resistivity for pure iron wire at 20°C (78°F) is 0.006.[10] For a 1°C change in temperature at 20°C, the following resistance sensitivity is obtained for a bridge with 25 ohms in each arm:

$$R_2 - R_1 = (25)(0.006)(1) = 0.15 \text{ ohms/}^{\circ}\text{C} \tag{2}$$

This resistance change in one arm has the following effect on the bridge balance:



R_1 = fixed resistors and jacket winding resistance, 25 ohms.

R_2 = column winding resistance (variable).

E = bridge supply voltage, 7 volts.

e = bridge unbalance in mv.

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[9]Eshbach, <u>op. cit.</u>, pp. 8-14, 8-66.

[10]Eshbach, <u>op. cit.</u>, pp. 1-125.

$$I_1 = \frac{E}{2R_1} \tag{3}$$

$$I_2 = \frac{E}{R_1 + R_2} \tag{4}$$

$$e \times 10^{-3} = R_2\left(\frac{E}{R_1 + R_2}\right) - R_1\left(\frac{E}{2R_1}\right)$$

$$e \times 10^{-3} = E\frac{(R_2 - R_1)}{(R_2 + R_1)} \tag{5}$$

Since a bridge unbalance of approximately 0 to $\pm$ 1 millivolt extends over the full control range, the change in resistance necessary to demand this full control may be found by substitution in formula (5).

$$1 \times 10^{-3} = 7\frac{(R_2 - 25)}{(R_2 + 25)}$$

$$R_2 = 25.007 \text{ ohms}$$

$$\Delta R = 0.007 \text{ ohms}$$

From equation (2) the maximum temperature differential is found to be:

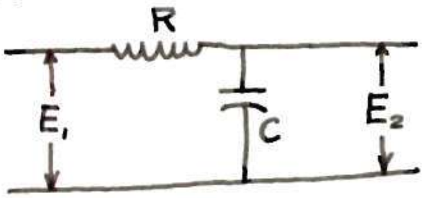
$$\Delta T = 1 \times \frac{0.007}{0.15}$$

$$= 0.047^{\circ}C$$

In other words, if the bridge is balanced perfectly under ambient conditions, the maximum possible temperature differential between the jacket and the column will be $0.047^{\circ}C$ while the temperature control system is in operation.

The bridge error signal is fed directly into the grid of the high gain amplifier. The amplifier has a measured gain of 70,000 and a maximum unclipped voltage output of about 50 volts. Since the amplifier input could not be measured directly on any available meters, the coarse balancing potentiometer on the resistance bridge was used to provide a bridge unbalance of measurable magnitude, then the input to the amplifier was stepped down by a voltage divider. It is extremely difficult to calculate the gain of a pentode amplifier through circuit analysis because of the variable tube characteristics; therefore, the measured gain of the amplifier has been accepted without theoretical proof. As previously mentioned, the measured gain checks closely with the tabulated values for the gain of a typical RC amplifier employing 6SH7 tubes.

After passing through the amplifier, the fraction of a millivolt has been amplified to a sufficient magnitude to be used as a controlling element. Unfortunately, the phase of the error signal is shifted about 30 degrees leading as it passes through the amplifier. Since the error signal must be in phase with the thyratron anode potential (line voltage) if the grid phase-shift control is to function properly, the input signal was shifted to 30 degrees lagging by an RC filter on the bridge supply voltage.



$R = 750$ ohms

$C = 2$ microfarads

$\omega = 377$ radians/sec.

$$E_2 = E_1 \left(\frac{-jx_c}{R - jx_c} \right)$$

$$= E_1 \left(\frac{-j1325}{750 - j1325} \right)$$

$$= E_1 (0.868 \angle -29.5^\circ)$$

The amplified error signal, now in phase with the thyratron anode voltage, was added to a fixed potential of 5 volts which lagged the anode voltage by 90 degrees. The vector sum of the two voltages constituted the grid potential on the thyratrons. Depending upon the phase and magnitude of the error signal, the grid voltage on the thyratrons could be varied from 5 volts at -90 degrees to about 60 volts at -5 degrees or -175 degrees. The combination of voltages was introduced into the grid circuit through 1 to 1 ratio high impedance transformers in order to isolate the voltages from a common ground.

The characteristic of the FG-27A thyratron tube is such that each tube will pass a maximum average anode current of 2.5 amperes at a critical grid breakdown voltage of -2.25 volts for an anode potential of 100 volts. Since the minimum tube voltage drop is 10 volts, the inverse parallel tubes of the thyratron power unit can supply a maximum of 5 amperes at 105 volts when operating from a 115 volt a-c supply.

The voltage and current supplied by the thyratrons is in the form of sine wave sections or pulses and is, therefore, useful only where average power is required regardless of wave form. The average value of current and voltage for each tube over one cycle may be determined from the following integration:

$$I = \frac{1}{2\pi} \int_{\phi}^{\pi} I_m \sin(wt)\, d(wt)$$

$$E = \frac{1}{2\pi} \int_{\phi}^{\pi} E_m \sin(wt)\, d(wt)$$

where ϕ = firing angle of thyratrons.

ω = angular frequency, radians/sec.

t = time in seconds.

I_m and E_m = maximum values of current and voltage.

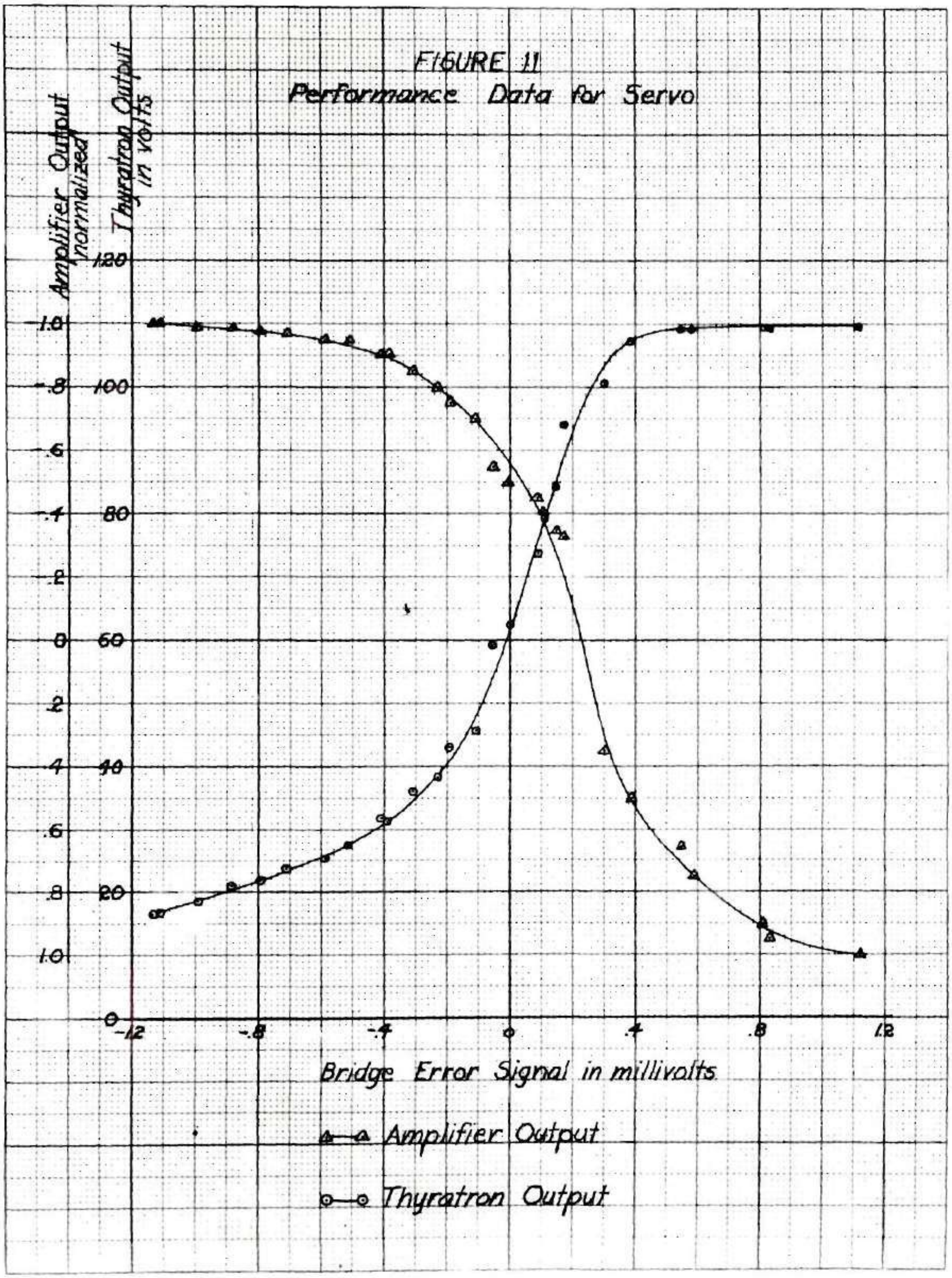


FIGURE 11
Performance Data for Servo
Amplifier Output normalized
Thyratron Output in volts
120
1.0
.8
100
.6
.4
80
.2
0
60
.2
.4
40
.6
.8
20
1.0
0
-1.2
-.8
-.4
0
.4
.8
1.2
Bridge Error Signal in millivolts
Amplifier Output
Thyratron Output

CHAPTER V

DISCUSSION OF RESULTS

The specific objective of this thesis project has been accomplished. The electronic servomechanism discussed in this paper automatically controls the temperature of the heater jacket within 0.047 degrees centigrade of the temperature of the fractional distillation column for all the specified conditions of column operation. The servo unit can replenish heat losses to the column within the range of 13 watts to 630 watts. The range of control and the accuracy of control are such that the column operation is essentially adiabatic. Examination of the servo performance curve (Figure 11) of input versus output voltage illustrates the degree of control obtained for various error signals. The steep slope of the curve near bridge balance and the almost linear relation on either side of the balance point indicates the high sensitivity and smooth control obtained from the system.

Furthermore, the servo unit is conveniently mounted on a self supporting panel with each separate unit individually mounted and connected by plugs and a wire harness (see Figure 12). The entire unit is self contained except for the 115 volt a-c supply. The output voltage of the servo is continuously indicated on the voltmeter mounted on the resistance bridge unit. The bridge balancing potentiometers are mounted directly underneath the voltmeter which indicates bridge unbalance. Each individual unit of the servo has a snap-on cover (see Figure 13) which provides easy access to all component parts as well as presenting a neat outward appearance and affording protection to the components.

Although the servo presents a pleasing appearance and does provide

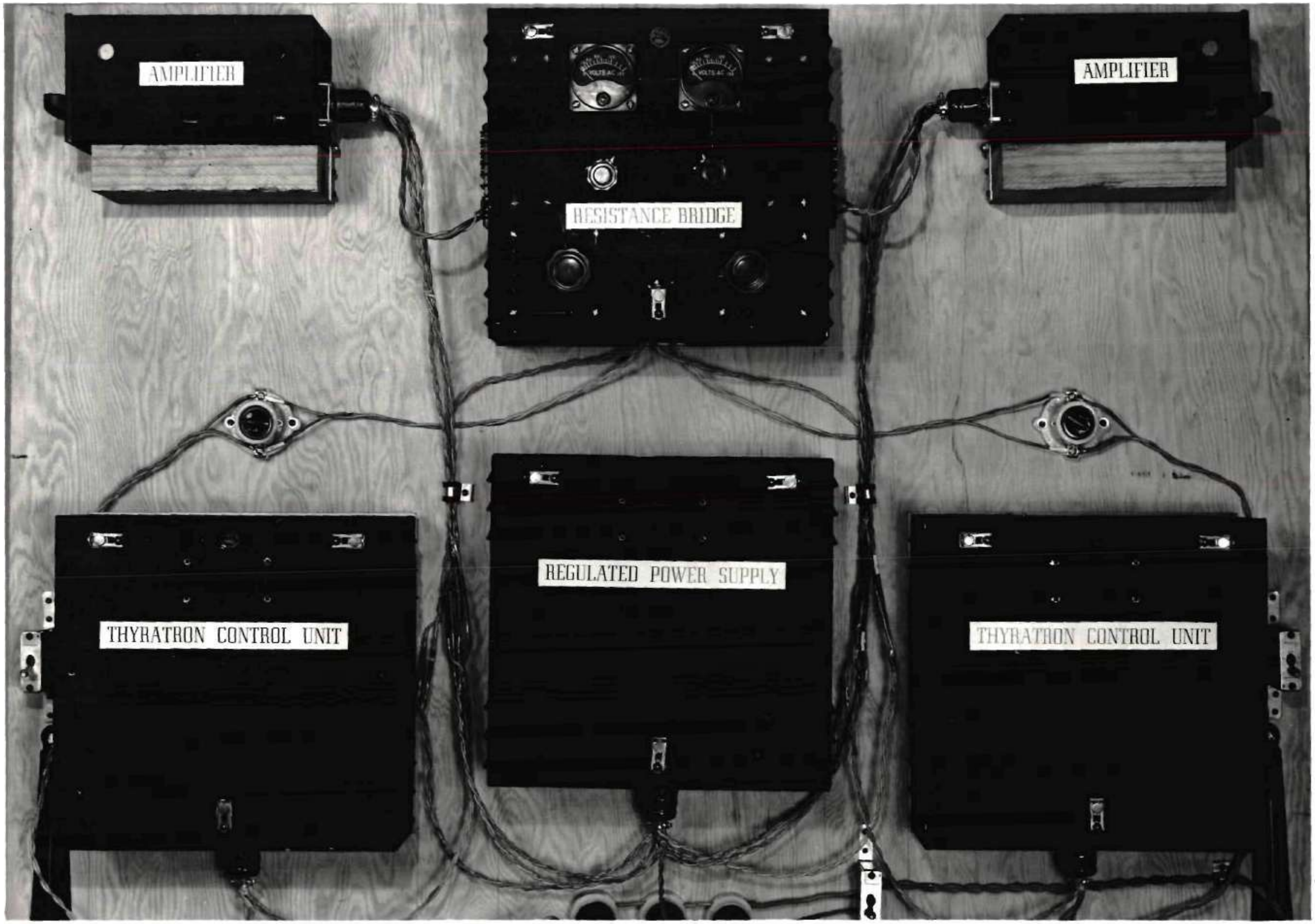

AMPLIFIER
RESISTANCE BRIDGE
AMPLIFIER
REGULATED POWER SUPPLY
THYRATRON CONTROL UNIT
THYRATRON CONTROL UNIT

FIGURE 12

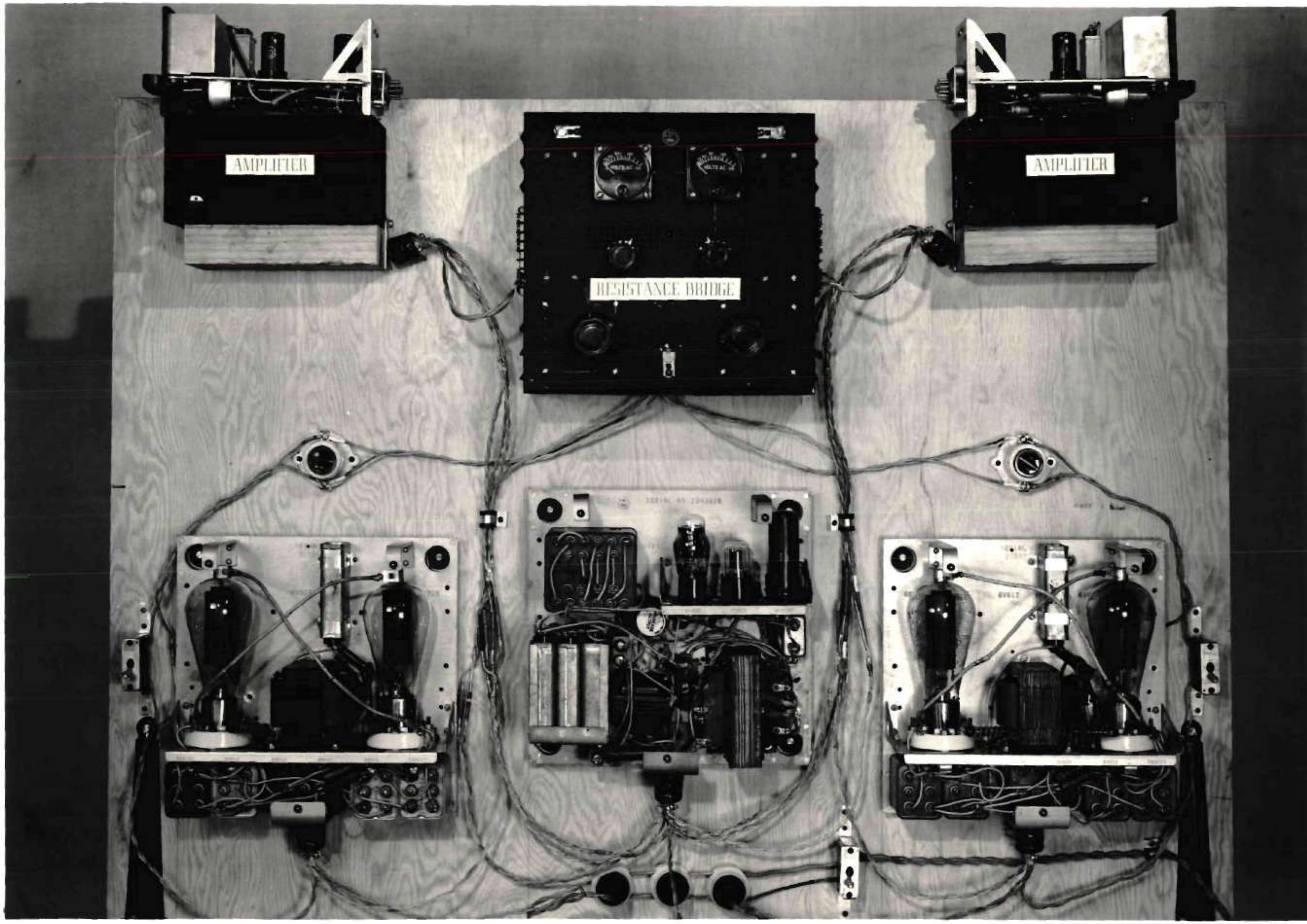


FIGURE 13

satisfactory control of temperature, its operation is not completely satisfactory. The amplifier output for signals inputs at or near zero is extremely distorted and full of "hash". Also, for zero signal input, the amplifier output is approximately 4 volts when it should be zero. This stray pickup and noise voltage seems to be unaffected by further shielding. The noise voltage in the amplifier output disturbs the smooth control at or near bridge balance.

An undesirable interaction between the top and bottom column control units is also present. As one control unit increases its output, the other unit tends to follow this increase for several volts before it returns to its original position. This interaction is thought to occur through the common amplifier filament and plate voltage supplies.

The reliability of the servo unit should be excellent since none of the component parts are operated at or near design limits. However, no extended test runs have been made.

CHAPTER VI

SUMMARY

The specific objective of this thesis project was to match the temperatures of a distillation column and its surrounding jacket in order to prevent heat transfer from the column. This was accomplished as follows: First, the columns were wound with wire having a high temperature coefficient of resistivity to convert the temperature into an electrical quantity, resistance. These windings were then placed in opposite arms of a resistance bridge for comparison. The error signal from the bridge was amplified to a controlling magnitude by an RC coupled amplifier. This amplified error signal was fed into the grid circuits of two thyratrons connected in inverse parallel. The amplified error voltage was added to a fixed voltage in such a way as to shift the phase and magnitude of the grid-to-cathode potential of the thyratrons. Thus grid phase-shift control of the thyratrons was obtained over a voltage range of from 15 volts to 105 volts. This thyratron output provided power to the heater coils on the jacket so as to replenish any heat losses from the column in the range of from 13 watts to 630 watts.

The maximum temperature differential that may occur between the column and the surrounding jacket is in the order of 0.047 degrees centigrade. Thus, the heat transfer between the two columns is essentially zero.

The servo operation is not completely satisfactory, particularly at extremely small error corrections, because of high level noise output of the amplifier. However, the desired control has been obtained with greater accuracy than manual control of the temperature difference could

accomplish and the servo replaces one man and several pieces of electrical equipment all of which can be utilized elsewhere in the column operation.

CHAPTER VII

RECOMMENDATIONS

Since one of the problems encountered in the operation of the servo control unit was the corrosion of the temperature sensitive windings, it is recommended that nickel wire be used instead of the pure iron. The sensitivity of the system will be decreased somewhat, but the nickel windings should be highly corrosive-resistant and therefore more reliable.

It is further recommended that an amplifier with lower noise characteristics be designed for use in the servo loop. The 6SH7 tubes are evidently very noisy. It is thought that the use of separate power supplies for the two amplifiers would eliminate the interaction between servo units.

This same servo unit may be utilized in other control applications simply by modifying the error sensing device. Pressures, fluid levels and many other physical characteristics may be matched or regulated by such a system.

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APPENDIX

CALCULATION OF HEAT TRANSFER FROM COLUMN

Heat transfer from the column occurs by convection and radiation, neither of which is negligible, and the total loss may be calculated by the following equation.[11]

$$q = h_c A_s (t_s - t_a) + h_r A_s (t_s - t_e)$$

where A_s = outside surface area, ft.^{2}

t_s = temperature of surface of body, $^\circ$F.

t_a = temperature of air, $^\circ$F., between jackets.

t_e = temperature of enclosing wall, $^\circ$F.

h_c = heat transfer coefficient for convection, BTU/ft.^{2}/hr./$^\circ$F.

h_r = heat transfer coefficient for radiation, BTU/ft.^{2}/hr./$^\circ$F.

For extreme conditions, the operating temperature of the column is 450°F. (200°C). This establishes the temperature of the column jacket to be 450°F. if satisfactory column operation is to be obtained. Assuming an ambient temperature of 70°F., it is estimated that the temperature of the enclosing wall or jacket surrounding both the column and heating jacket will be 200°F. Since the diameter of the enclosing jacket is 62 mm. and the height of jacket is 4 feet,

$$A_s = \pi dh$$
$$= \pi \left(\frac{6.4}{2.54 \times 12}\right) 4 = 2.64 \text{ ft.}^2$$

---

[11] W. H. McAdams, Heat Transmission (New York: McGraw-Hill Book Company, Inc., 1942), p. 240.

Also for vertical pipes more than 1 foot high,[12]

$$h_c = 0.27 \left(\frac{\Delta t}{D_o}\right)^{0.25} \quad \text{where } D_o = \text{diameter of enclosing wall in ft.}$$

$$= 0.27 \left(\frac{130}{0.21}\right)^{0.25}$$

$$= 1.35 \ \text{BTU/ft.}^2\text{/hr./}^\circ\text{F.}$$

$$h_r = 1.5 \ \text{BTU/ft.}^2\text{/hr./}^\circ\text{F.} \quad \text{from Figure 27.}^{13}$$

Since $t_a \doteq t_e$

$$q = (h_c + h_r)\, A_s\, (t_s - t_a)$$

$$= (1.35 + 1.5)(2.64)(130)$$

$$= 1020 \ \text{BTU/hr.} = 300 \ \text{Watts}$$

Therefore 300 watts is the heat lost to the atmosphere by the enclosing wall.

The heat loss of the heater jacket is as follows:

$$A_s = \pi\, dh \quad \text{where } d = 48 \text{ mm.}, \ h = 4 \text{ feet}$$

$$= 0.16 \ \text{ft.}^2$$

$$h_c = 0.27 \left(\frac{250}{0.16}\right)^{0.25}$$

$$= 2 \text{BTU/ft.}^2\text{/hr./}^\circ\text{F.}$$

$$h_r = 2.7 \text{BTU/ft.}^2\text{/hr./}^\circ\text{F.} \quad \text{(Figure 27)}^{13}$$

$$q = (2 + 2.7)(0.16)(250)$$

$$= 2360 \ \text{BTU/hr.}$$

$$= 693 \ \text{watts}$$

---

[12] Ibid, p. 241.

[13] Ibid, p. 63.

The heat loss from the jacket under extreme operating conditions is, therefore, 693 watts. The 393 watts unaccounted for in heat transfer from the heater jacket to the enclosing wall is considered to have been conducted away by the metal base and cap of the column. In practice, the enclosing wall would probably be at a higher temperature, thus reducing the heat losses from the heater jacket, but the most extreme temperature conditions expected were considered in these calculations.

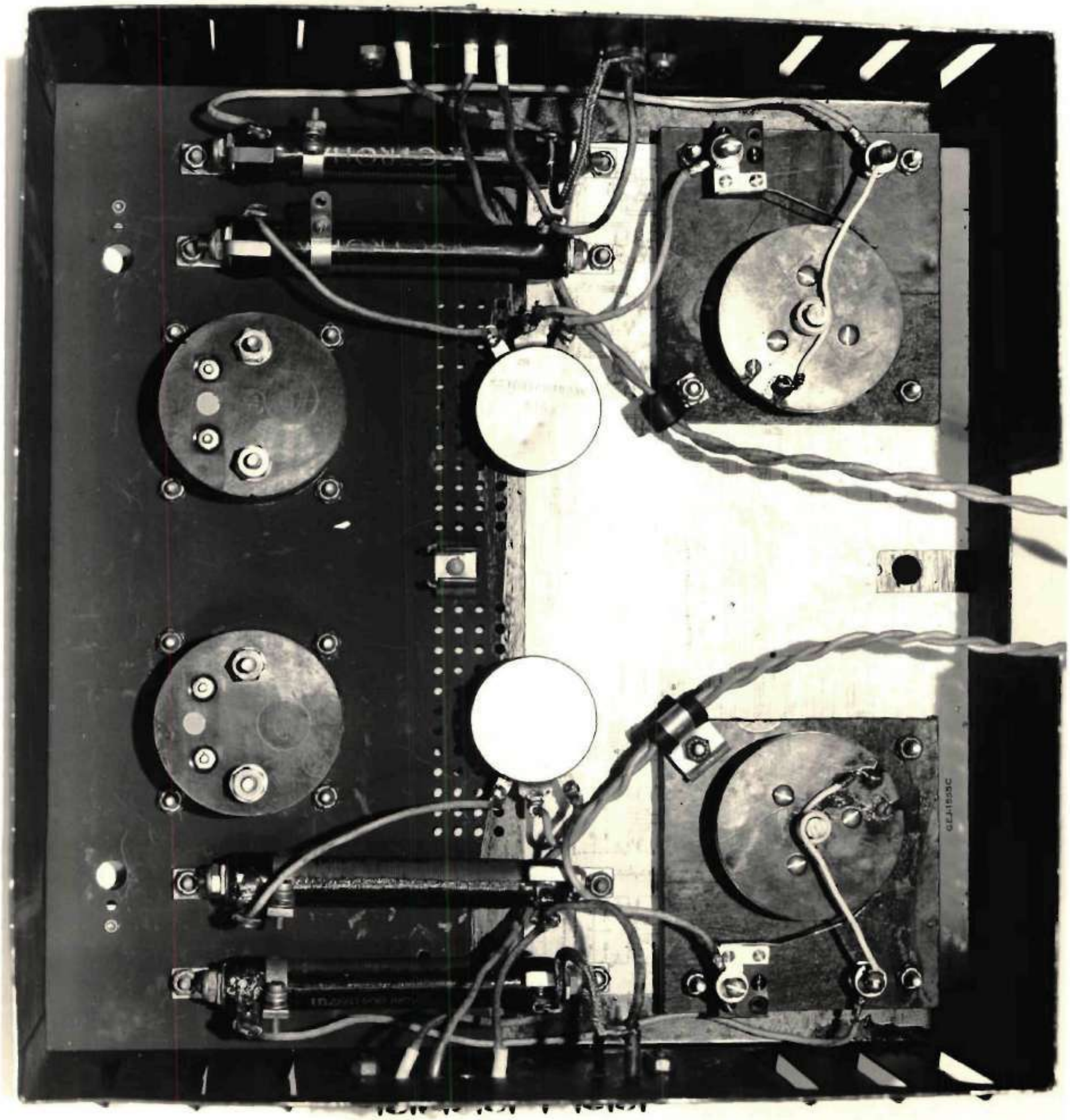

FIGURE 14

RESISTANCE BRIDGE, REAR VIEW

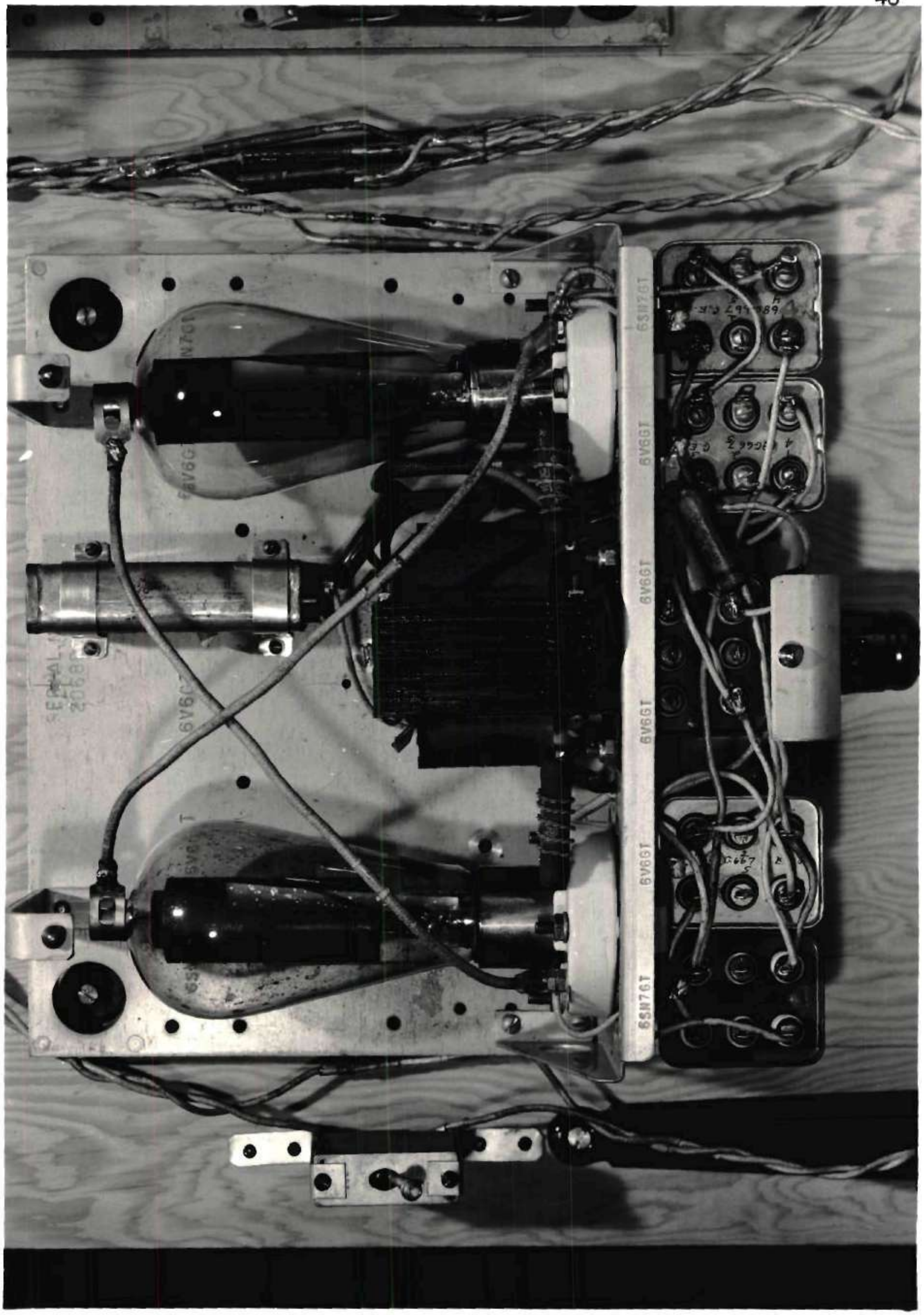

FIGURE 15
THYRATRON CONTROL UNIT, CLOSE-UP VIEW

SERVO PERFORMANCE DATA

(Refer to Figure 11)

Error Signal from Bridge (mv.)	Amplifier Output (normalized)	Thyratron Output (volts)
-1.133	-1.00	16.5
-1.115	-1.00	16.8
-0.991	-0.99	18.5
-0.885	-0.99	20.8
-0.796	-0.98	21.8
-0.708	-0.97	23.8
-0.584	-0.95	25.3
-0.513	-0.95	27.7
-0.407	-0.90	32.0
-0.389	-0.90	31.2
-0.301	-0.85	36.0
-0.230	-0.80	38.1
-0.195	-0.75	43.0
-0.106	-0.70	45.7
-0.053	-0.55	59.2
0.000	-0.50	62.5
0.089	-0.45	73.7
0.106	-0.40	79.5
0.142	-0.35	84.4
0-177	0.33	94.0
0.301	0.35	100.5
0.389	0.50	107.3
0.549	0.65	109.2
0.584	0.75	109.2
0.814	0.90	109.4
0.832	0.95	109.3
1.115	1.00	109.4

CIRCUIT COMPONENTS

I <u>Resistance Bridge Components</u> (refer to Figures 5 and 6)

R_1 - Column temperature sensitive winding, 25 ohms approximately.
R_2 - Jacket temperature sensitive winding, 25 ohms approximately.
R_3 - 25 ohms wire wound resistor.
R_4 - 25 ohms wire wound resistor.
R_5 - 750 ohms.
1P - 3 ohm potentiometer.
2P - 0.15 ohm rheostat.
C_1 - 2 microfarads.
1T - 115 v. a-c filament transformer.

II <u>Amplifier Components</u> (refer to Figure 7)

Tube 1 - 6SH7
Tube 2 - 6SH7
Tube 3 - 6J5

R_1 - 0.1 megohm	C_1 - 1.0 microfarads
R_2 - 0.47 megohm	C_2 - 23 microfarads
R_3 - 3000 ohms	C_3 - 0.1 microfarads
R_4 - 1.2 megohm	C_4 - 0.1 microfarads
R_5 - 1.2 megohm	C_5 - 23 microfarads
R_6 - 0.47 megohm	C_6 - 0.1 microfarads
R_7 - 3000 ohms	C_7 - 0.1 microfarads
R_8 - 1.2 megohms	C_8 - 0.1 microfarads
R_9 - 1.2 megohms	
R_{10} - 2000 ohms	
R_{11} - 20,000 ohms	

III <u>Thyratron Components</u> (refer to Figure 9)

Tube 1 - FG-27A
Tube 2 - FG-27A
1T - 115 v. a-c transformer, two 5.8 volt filament windings, one center-tapped 11.6 volt winding.
2T -)
3T -) 1 to 1 ratio high impedance transformers. 68G667.
4T -)
5T -)

R_1 - 1000 ohms	C_1 - 3 microfarads, C_2 - 0.01 microfarads
R_2 - 0.18 ohm	L_1 - 68G667 transformer used as inductance coil.
R_3 - 0.18 ohm	
R_4 - 10,000 ohms	
R_5 - 10,000 ohms	
R - 35 ohms	

IV <u>Power Supply Components</u> (refer to Figure 10)

Tube 1 - 5Y3
Tube 2 - 6L6
Tube 3 - 6SL7
Tube 4 - VR105
Tube 5 - 6SL7
1T - 115 v. a-c high voltage transformer.
1 - 800 volt center-tapped winding.
1 - 5 volt filament winding.
3 - 6.3 volt filament winding.

R_1	- 560,000 ohms	R_8	- 220,000 ohms
R_2	- 10,000 ohms	R_9	- 500,000 ohms
R_3	- 180 ohms	R_{10}	- 560,000 ohms
R_4	- 1,000 ohms	R_{11}	- 10,000 ohms
R_5	- 500,000 ohms	R_{12}	- 10,000 ohms
R_6	- 10,000 ohms	1P	- 0 to 25,000 ohms potentiometer
R_7	- 500,000 ohms		
C_1	- 3 microfarads	C_4	- 0.1 microfarads
C_2	- 12 microfarads	C_5	- 3 microfarads
C_3	- 0.1 microfarads		

L_1 - 68G668X transformer used as filter choke.

PLUG CONNECTIONS AND COLOR CODING

I Resistance Bridge

(1) 7 volts a-c, orange
(2) 7 volts a-c, clear or dark green

II Amplifier

Plug terminal
(1) B-, ground - - - - - - - - - - - green
(2) B+, 250 v. d-c - - - - - - - - - yellow
(3) blank
(4) blank
(5) filament, 6.3 v. a-c - - - - - - red
(6) output - - - - - - - - - - - - - red and black
(7) filament, 6.3 v. a-c - - - - - - black
(8) blank
(9) ground - - - - - - - - - - - - - orange
(10) input - - - - - - - - - - - - - shielded
(11) ground - - - - - - - - - - - - - orange

III Thyratron Unit

Plug terminal
(1) 110 v. a-c - - - - - - - - - - - plug
(2) 110 v. a-c - - - - - - - - - - - plug
(3) output, 15 to 105 v. a-c - - - socket
(4) output, 15 to 105 v. a-c - - - socket
(5) blank
(6) blank
(7) blank
(8) blank
(9) blank
(10) grid signal from amplifier - - red and black
(11) ground - - - - - - - - - - - orange

IV Power Supply

Plug terminal
(1) 110 v. a-c - - - - - - - - - - - plug
(2) 7 v. a-c - - - - - - - - - - - - orange
(3) B+, 250 v. d-c - - - - - - - - - yellow
(4) filament, 6.3 v. a-c - - - - - - red
(5) 7 v. a-c - - - - - - - - - - - - orange
(6) B-, ground - - - - - - - - - - - green
(7) 7 v. a-c - - - - - - - - - - - - dark green
(8) filament, 6.3 v. a-c - - - - - - black
(9) B+, 250 v. d-c - - - - - - - - - yellow
(10) 7 v. a-c - - - - - - - - - - - - clear
(11) 110 v. a-c - - - - - - - - - - - plug